Non-Invasive Assessment of Direction of Right Atrial Activation During Atrial Fibrillation Using Correlation Function Analysis

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Abstract

ECGs were recorded from three electrodes attached at the corners of an equilateral triangle positioned around the location of electrode V1. The atrial signal between QRST complexes was subjected to correlation function analysis to reveal differences in activation times between the electrode sites. The time differences found were used to calculate the direction of activation across the body surface. Twenty-three subjects were studied during sinus rhythm (SR), intraoperatively confirmed typical and reverse typical atrial flutter, or during paroxysmal or permanent atrial fibrillation (AF).

Subjects studied during SR and patients with typical atrial flutter exhibited a uniform direction of activation, with the main vector pointing downwards. The propagation of atrial activation during permanent AF did not show a consistent direction, while patients with paroxysmal AF exhibited more uniform activation vectors, corresponding to the direction observed in patients with atrial flutter.

1. Introduction

Atrial fibrillation (AF) is the most common form of arrhythmia encountered in clinical practice, accounting for approximately one third of hospital admissions for cardiac rhythm disturbances [1]. Findings in recent, randomized, clinical trials [2, 3, 4] have highlighted the need for the analysis of the characteristics of atrial electrophysiology in each patient with AF, in order to increase the chance of success, regardless of the treatment strategy chosen. Given the large number of patients with AF, characterization must be possible using an easily administered and interpreted method, i.e., a non-invasive approach is required.

A non-invasive method for extracting an index of atrial refractoriness from the ECG has been developed [5, 6, 7, 8], and its possible clinical merits demonstrated [9, 10]. However, not only atrial refractoriness is of potential clinical importance. In experimental studies, the directions and degree of uniformity of the electrical propagation during AF have been shown to vary according to the clinical severity of the arrhythmia [11, 12, 13]. Little is known about the ECG characteristics of normal and abnormal intra- and interatrial conduction propagation during AF.

Knowledge of the direction of atrial activation during AF may be important not only for the characterization of arrhythmia, but also for tailoring AF ablation procedures. The aim of the present study was to describe the direction of atrial activation during AF non-invasively, using correlation function analysis.

2. Methods

2.1. Subjects

Three patients with atrial flutter (one reverse typical, two typical), four with paroxysmal AF and eleven patients with permanent AF were included in the study. Recordings were made during atrial arrhythmia in all subjects. Five healthy volunteers were included as a control group and were examined during sinus rhythm. Of the 18 patients and 5 controls, 21 were males and their mean age was 69 ± 11 years.

2.2. Data acquisition

Three electrodes were positioned at the cormers of an equilateral triangle around the position of Lead V1, see Figure 1. The length of the triangle's sides was 12 cm. Signals from these electrodes were sampled simultaneously at 1000 Hz with a resolution of 0.625 μV, and stored in data files for off-line processing.

The signals were recorded using standard 12-lead ECG recording equipment with WCT as the reference. The signals were collected via the inputs normally used for Leads V1-V3.

2.3. Extracting atrial signals

The onset and end of all QRST segments were identified automatically, but with the option of manual override.

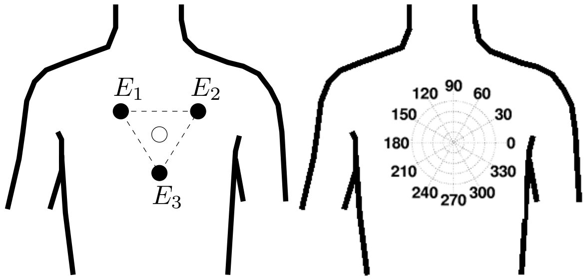

Figure 1. *Left:* Electrode positioning. The circle indicates the standard position of Lead V1. The black dots show the positions of the electrodes at the corners of an equilateral triangle with sides of length 12 cm. *Right:* Orientation of angles.

These segments were discarded in the subsequent analysis in order to only include a "pure atrial signal". In the case of AF and atrial flutter, the atrial signal segments between the end of each T wave and onset of the next Q wave were included if their lengths exceeded 200 ms. In the case of sinus rhythm, only the signal segments containing P waves were included.

2.4. Calculation of time delay between signals

Correlation function analysis was used to determine the time-delay between two signals. The correlation function between two signals, x and y, is defined as:

$$\rho(\tau) = \frac{C_{xy}(\tau)}{\sqrt{|C_{xx}(\tau)|}\sqrt{|C_{yy}(\tau)|}}$$

where

$$\tau = -n, \ldots, -1, 0, 1, \ldots, n$$

is the time delay in milliseconds (samples). In this study, the maximum time delay analyzed, n, was 20 ms.

The sample covariances are defined as:

$$C_{xy}(\tau) = \frac{1}{N-\tau} \sum_{i=1}^{N-\tau} \left(x_{i+\tau} - \overline{x}_{1+\tau,N}\right)\left(y_i - \overline{y}_{1,N-\tau}\right)^T$$

and the sample means as:

$$\overline{x}_{1,N-\tau} = \frac{1}{N-\tau} \sum_{i=1}^{N-\tau} x_i$$

and

$$\overline{x}_{1+\tau,N} = \frac{1}{N-\tau} \sum_{i=1+\tau}^{N} x_i$$

Calculations were performed using signals from electrodes E_1 and E_2, and electrodes E_1 and E_3. The time delays obtained were denoted $t_{E_1E_2}$ and $t_{E_1E_3}$.

2.5. Calculating impulse direction

When calculating and presenting the direction of impulse conduction in relation to the body, the coordinate system shown in Figure 1 was used. It is assumed that there is only one, plane wave in the area, and that it is moving at a uniform velocity.

To calculate the angle of impulse conduction, α, when $t_{E_1E_2}$ or $t_{E_1E_3}$, were 0, the following algorithm was used:

- If $t_{E_1E2} = 0$ and $t_{E_1E_3} = 0$ the angle cannot be defined and $\alpha = 0$.
- If $t_{E_1E_2} = 0$

$$\alpha = \begin{cases} 90^\circ, & \text{if } t_{E_1E_3} < 0 \\ 270^\circ, & \text{if } t_{E_1E_3} > 0 \end{cases}$$

and

- If $t_{E_1E_3} = 0$

$$\alpha = \begin{cases} 210^\circ, & \text{if } t_{E_1E_2} < 0 \\ 30^\circ, & \text{if } t_{E_1E_2} > 0 \end{cases}$$

In all other cases, the direction of impulse conduction can be calculated as the direction of the normal vector to the two velocity vectors $v_{E_1E_2}$ and $v_{E_1E_3}$ (Figure 2). Let the vector r be defined by the two velocity vectors

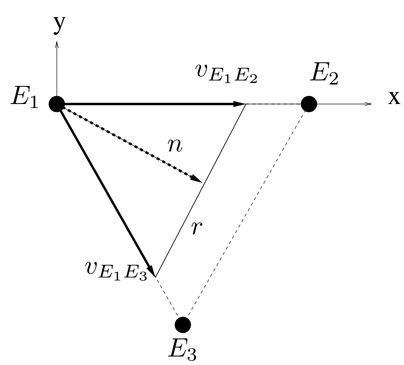

Figure 2. The vector r is defined by the velocity vectors $v_{E_1E_2}$ and $v_{E_1E_3}$. The direction of impulse conduction is equal to the normal vector to r.

$v_{E_1E_2} = (x_1, y_1)$ and $v_{E_1E_2} = (x_2, y_2)$. Let the vector $n = (a, b)$ be the vector normal to r. a and b can then be calculated from

$$a(x_2 - x_1) + b(y_2 - y_1) = 0$$

which yields a parametric solution, for example:

$$\begin{aligned} a &= 1 \\ b &= \tfrac{x_2 - x_1}{y_2 - y_1} \end{aligned}$$

The direction of conduction can be calculated from a and b using the MATLAB command `cart2pol`, which performs transformations from the Cartesian to the polar coordinate system.

The angle of conduction was calculated from each signal segment of the recordings. The results are presented in angle histogram plots using the MATLAB command `rose`.

3. Results

In the recordings made in four of five healthy controls during sinus rhythm, conduction was consistently directed downwards and leftwards, with angles between 300° and 330°; two cases are illustrated in Figure 3. In the fifth case, conduction was directed downwards, with angles between 240° and 270°.

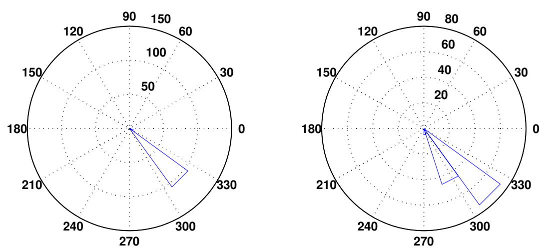

Figure 3. Results obtained from data recorded during sinus rhythm in two of the controls. (For the orientation of the angles, see Figure 1)

In the recordings made during atrial flutter, the direction of conduction was also found to be very consistent, with angles between about 240° and 270° in the cases of typical atrial flutter, and between 60° and 120° in the case of reverse typical atrial flutter (both illustrated in Figure 4).

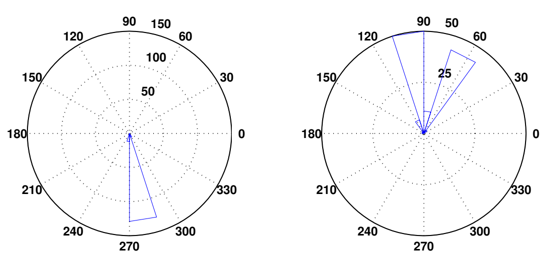

Figure 4. Results obtained from data recorded during typical atrial flutter (left), and reverse typical atrial flutter (right).

The recordings obtained in cases of paroxysmal AF showed an lower degree of uniformity in conduction direction than in the cases of sinus rhythm and atrial flutter but, as illustrated in Figure 5, a dominant direction could still be seen.

The recordings made in the subjects with permanent AF showed a lower degree of uniformity than in the subjects with paroxysmal AF. As can be seen from Figure 6, it is difficult to discern a dominant direction of conduction.

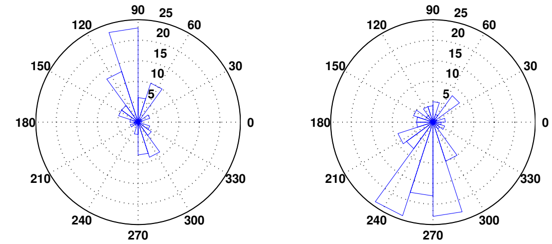

Figure 5. Results obtained from data recorded during paroxysmal atrial fibrillation in two of the subjects. Although less uniform than those for sinus rhythm and atrial flutter, a dominant direction of conduction can still be seen.

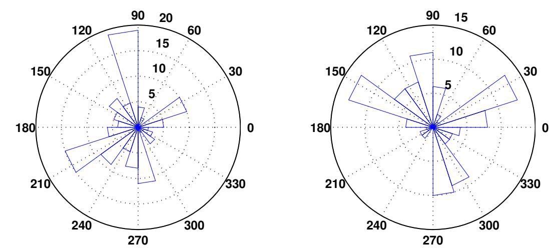

Figure 6. Results obtained from data recorded during permanent atrial fibrillation. No dominant conduction direction can be discerned.

4. Discussion and conclusions

The finding of a uniform direction of conduction downwards and leftwards, in control subjects examined during sinus rhythm is expected, given the location of the sinus node in the high right atrium.[14] The pattern observed in the two patients examined during typical atrial flutter and the opposite direction found in the single patient with reverse typical atrial flutter, also indicate that the method is indeed able to determine the direction of right atrial conduction. It is reasonable to believe that the method may also be used to determine conduction directions in other types of arrhythmia.

The findings during atrial fibrillation are, not surprisingly, characterized by a less uniform conduction pattern than that observed during sinus rhythm and atrial flutter. However, although less uniform, the major activation routes seem to be unaffected, with the main vector being similar to either sinus rhythm, typical atrial flutter or reverse atrial flutter. An intriguing finding is the apparent difference between activation patterns in patients with paroxysmal and permanent atrial fibrillation. It can be speculated, that these differences may reflect different degrees of electrical remodeling, a phenomenon of increasing disorganization as arrhythmia duration increases, well known in atrial fibrillation.[15] This finding must be quantified and confirmed in a larger study.

This non-invasive, easily available method may, in the future, be valuable in the clinical setting as a tool for improved arrhythmia characterization. Although it remains to be tested, the method may also generate important prognostic information in regard to the success of cardioversion of atrial fibrillation, and sinus rhythm maintenance. It may also serve as a tool for monitoring atrial electrophysiology during ablation procedures.

An obvious limitation of the study is that only "pure" atrial signal segments longer than 200 ms can be used. A future study should evaluate whether some method of QRST cancellation could allow the whole signal to be analyzed.

We have presented a non-invasive method of assessing the direction of propagation of atrial activation during AF, which was validated in patients with known atrial activation patterns. Differences in the direction of propagation of right atrial activation were observed in a limited number of subjects with paroxysmal and permanent AF and warrant further research.

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